Evolving Emotional Behaviour in Autonomous Agents for Expressive Performance of Music

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Abstract. This paper describes a model for simulating emotional behaviour in autonomous agents, for expressive performance of music. It aims to model part of the emotional process where self-survival tasks and "embodiment" influence behaviour and affective states. The model consists of a population of agents with complex cognitive, emotional, and behavioural abilities. Agents inhabit an environment where they can interact with several objects related to their emotional system. This considers the role of emotions as part of the homeostatic mechanisms. An agent internal body state is defined by a set of physiological variables that vary accordingly to their interaction with the world, and a set of internal drives. The agent is controlled by a feed-forward neural network that integrates visual input and information on its internal and emotional states to interact with objects and explore the world. The network learns through a reinforcement learning algorithm.

1 Introduction

The importance of Emotions has been emphasized throughout the years in several areas of research. They seem to have an important role in behaviour and adaptation in biological systems. Several are the findings that point to the surprising role of emotions in intelligent behaviour, coming from neuroscience, psychology, and cognitive sciences, etc. An interesting path has been traced by several researchers, looking to the physiological interferences, and the relation between body and affective states, as well to evolutionary mechanisms. We share the neurobiological and evolutionary perspectives to emotions [1].

1.1 How do we define Emotions?

Going back to the 19^{th} century we find the earliest scientific studies on emotions: Charles Darwin [2] observations about bodily expression of emotions, William James [3] seek for the meaning of emotion, and Wilhelm Wundt [4] who defended the importance of including emotions among the research topics in psychology studies. But for many years, studies on behaviour focused on higher level processes of the mind, discarding emotions [5]. Still emotions were discussed, and the ideas changed considerably throughout time. The line connecting mind and body, and the interfering of emotions in rationality, came emphasized after Cannon [6]. They suggested that there are neural paths from our senses that go in two directions - the experience of an emotion, and the physiological responses occur together. Later Tomkins [7], Plutchik [8] and Izard [9, 10]developed similar versions for evolutionary theories of emotions. They claimed that emotions are a group of similar processes of certain brain structures and that each of these has a unique concrete emotional content, reinforcing their importance. Paul Ekman proposes the basic (and universal) emotions [11], based on cross-cultural studies [12]. These ideas were widely accepted in evolutionary, behavioural and cross-cultural studies, by their proven ability to facilitate adaptive responses. Important insights come from Antonio Damasio [13][1][14], who brings to the discussion some strong neurobiological evidence, mainly exploring the connectivity between body and mind. suggests that, the process of emotion and feeling are part of the neural machinery for biological regulation, whose core is formed by homeostatic controls, drives and instincts. Survival mechanisms are related this way to emotions and feelings, in the sense that they are regulated by the same mechanisms. For further details on Emotions, Cognition, and Behaviour, please refer to [15].

Arousal and Valence Most researchers agree that emotion has at least two qualities: valence (pleasantness or hedonic value) and arousal (bodily activation). Both may be defined as subjective experiences [16]. Valence is a subjective feeling of pleasantness or unpleasantness; arousal is a subjective state of feeling activated or deactivated. A two dimensional model has been proposed to reflect the degree to which different individuals incorporate subjective experiences of valence and arousal into their emotional experiences [17]. In Fig. 1, there is a possible representation of this two-dimensional space.

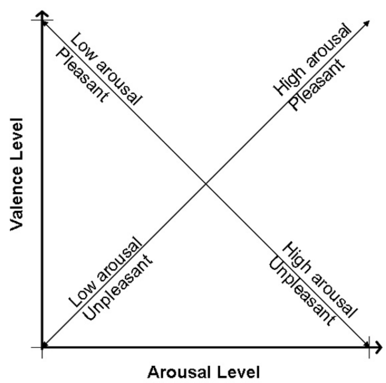

Fig. 1. Arousal-Valence Space.

1.2 Music and Emotions

The use of expressive marks by Western composers documents well the common assumption that emotions play an important role in music performance.

Expressive marks are performance indications, typically represented as a word or a short sentence written at the beginning of a movement, and placed above the music staff. They describe to the performer the intended musical character, mood, or emotion as an attribute of time, as for example, *andante con molto sentimento*, where *andante* represents the tempo marking, and *con molto sentimento* its emotional attribute.

Before the invention of the metronome by Dietrich Nikolaus Winkel in 1812, composers resorted to words to describe the tempo (the rate of speed) in a composition: Adagio (slowly), Andante (walking pace), Moderato (moderate tempo), Allegretto (not as fast as allegro), Allegro (quickly), Presto (fast). The metronome's invention provided a mechanical discretization of musical time by a user chosen value (beat-unit), represented in music scores as the rate of beats per minute (quarter-note = 120). However, after the metronome's invention, words continued to be used to indicate tempo, but now often associated with expressive marks. In some instances, expressive marks are used in lieu of tempo markings, as previous associations indicate the tempo being implied (e.g. *funebre* implies a slow tempo).

The core "repertoire" of emotional attributes in music remains short. Expressions such as *con sentimento*, *con bravura*, *con affetto*, *agitato*, *appassionato*, *affetuoso*, *grave*, *piangendo*, *lamentoso*, *furioso*, and so forth, permeate different works by different composers since Ludwig van Beethoven (1770-1827) . But what exactly do these expressions mean?

Each performer holds a different system of beliefs of what expressions such as *con sentimento* represent, as our understanding of emotions has not yet reduced them to a lawful behaviour. Without consensus on the individual meaning of such marks, a performance *con sofrimento* is indistinguishable from one *con sentimento*, since both expressions presume an equally slow tempo. Although we have no agreement on the meaning of expressive marks and their direct musical consequences, musicians have intuitively linked expressivity with irregularity within certain boundaries. Celebrated Polish pianist and composer Ignacy Jan Paderewski (1860-1941) stated: "every composer, when using such words as *espressivo*, *con molto sentimento*, *con passione*, and so on, demands (...) a certain amount of emotion, and emotion excludes regularity... to play Chopin's G major Nocturne with rhythmic rigidity and pious respect for the indicated rate of movement would be (...) intolerably monotonous (...). Our human metronome, the heart, under the influence of emotion, ceases to beat regularly - physiology calls it arrhythmic, Chopin played from his heart. His playing was not rational, it was *emotional*". [18].

Composers are well aware that a clear representation of the musical idea reduces ambiguity in the interpretation of the message (the music score). However, the wealth of shadings, accents, and tempo fluctuations found in human performances are, at large, left unaccounted by the composer as the amount of information required to represent these type of nuances carries, in practice, no linear bearing in the detail human performers can faithfully reproduce.

While the electronic and computer music mediums provide composers the power to discretize loudness and time related values in very small increments (for example, MIDI systems use 128 degrees of loudness, and time measured in milliseconds), we note that music scores for human performances use eight approximate levels of loudness (ppp, pp, p, mp, mf, f, ff, fff), and time is discretized in values hundreds of milliseconds long. If we compare any two "faithful" human performances of a work, we conclude that, from performance to performance, only the order of notes remains strictly identical.

Expression marks operate as synesthesia, that is, the stimulation of one sense modality to rise to a sensation in another sense modality [19]. Although their direct musical consequences remain unclear, we can deduce which musical levels are susceptible of being influenced: time and loudness.

These are structural levels where small value changes produce significantly different results. The amount of information needed to describe such detail in fine resolution falls outside the precision limits with which human performers process a music score to control time and the mechanics of traditional music instruments.

> "*Look at these trees!*" Liszt told one of his pupils, "*the wind plays in the leaves, stirs up life among them, the tree remains the same. That is Chopinesque rubato*[1]."

2 Polymnia: The Model

Due to a progressive change in theoretical studies in a broad range of areas, models of cognition, attention, and behaviour now frequently include emotions as part of the behavioural system. The idea that these states might influence actions is getting stronger and as gained special attention in computational models of cognition and behaviour [20–23].

2.1 The concept

We created a conceptual A-Life-like model to implement artificial world inhabited by autonomous agents. We focus on the autonomous agents biological structure in order to adopt an evolutionary perspective. We reinforce the idea of having an embodiment (in the sense that the agent has a virtual physical body) for the agents so that low level tasks (e.g. satiate body needs) influence their overall performance, by affecting behaviour. In this phase, emotions act as an adaptation mechanism, having in mind that the brain systems related to emotions are historically older than other areas. It implements the agents background structure that will allow us to contextualize the foreground emotional system (and

[1] *Rubbato*: from the Italian "robbed", used to denote flexibility of tempo to achieve expressiveness.

the so called Basic Emotions [11]), in order to define the agents's emotional state by locating it in the arousal/valence space (see Sec. 1.1).

2.2 The Artificial World

Polymnia consists in a two dimensional bitmap world populated by several objects (See Fig. 2). Agents inhabit this world, and they are able to move within its borders that define its limits. The objects represent different sources of elements for the agents (See Table 1). The agents perceive these objects through a circular retina (explained in Sec. 2.4). We also created obstacles in the world that, in the simplest case, are only the world limits; these are a source of pain to the agent. Summarizing, we have an agent that has to adapt itself to a world, by controlling self-survival tasks, and by attributing "emotional" meanings to objects (objects might have different meanings for different situations).

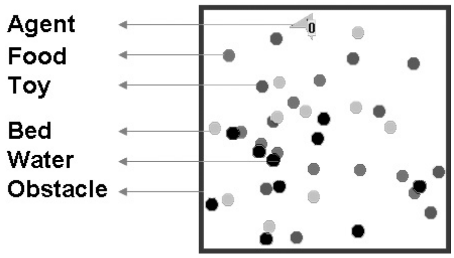

Fig. 2. Polymnia World.

Object Color	Representation	Physiological interference	Required Motivation
Red	Food	Increase Blood Sugar	Eat
Green	Bed	Increase Energy	Rest
Blue	Obstacles	Increase Pain	Any
White	Water	Increase Vascular Volume	Drink
Rose	Toy	Increase Endorphine	Play

Table 1. Objects representation and interferences.

2.3 The Agents

We developed a versatile structure for the agents, that allows us to improve it accordingly to the project development. This way we now focus on the individual level, and we divide it into three main parts: Cognitive System, Motor System, and Embodiment/Emotional System. Later on these structures will be developed to incorporate more complex interaction interfaces between agents, and more complex "objects".

2.4 Cognitive System.

The agents cognitive system consists on the perceptual and nervous subsystems. The **perceptual subsystem**, inspired in LIVIA [24] and GAIA [25]), contains a retina (here represented as a color array) as close as possible to a biological retina on a functional level. It senses a bitmap world through a *ray tracing* algorithm, which is inspired on the photons travel from the retina to the light-emitting objects. Each light ray that hits the sensing cells is traced to its origin in order to determine its intensity and colour, which feeds directly to the neural network. The **nervous subsystem** incorporates a feed-forward neural network (NN) with a fixed encoded structure. The neural network is organized by areas: an input area (two layers: retina and body sensors), an output area (two layers: motivations and motor control), and a hidden layer (with excitatory and inhibitory neurons). Each area has projections (a group of synapses) to any other area in the following layer.

2.5 Motor System.

Thinking about emotions and body, urges to the need of a interactive embodiment system. We created a simple structure for this: the agent controls a motor system through linear and angular speed signals, allowing it to travel around the world (including obstacle avoidance and object interaction). These signals are provided by the neural network, which means that motor skills also have to be learned.

2.6 Behavioural, Emotional, and Learning Systems.

We consider emotions (in one of their roles) as part of the Homeostatic mechanisms. Fig. 4, gives us an overview of the system workflow. As stated, the agent perceives its world through a retina, and this signals are used to feed a set of input layers in the NN, together with its internal body state. The body state consists in a map of the agents body (Physiological Variables: varying from a minimum to a maximum values), modulated by their Drives (see Fig. 4), that define the the current and past body states, by signaling urges to action towards specific needs. These last are calculated through an average for the associated Physiological Variables (see Table 2), within a 30 iterations interval ("temporary memory"). Our intention is to get the model closer to Biology, by introducing implicitly emotions latency.

As defined in Sec. 2.2, interacting with objects causes changes in the body state. But, as shown in Table 2, the environment changes also indirectly the agents body by means of its metabolism. Agent ongoing tasks (not interacting with objects) change its internal physiological data (corresponds to a decrease/increase in a physiological variable, accordingly to the metabolism - decrease blood sugar, increase pain, etc.). They include emotional amplification , in analogy to the Somatic Markers theory [13]. Each Drive, together with retina signals, are feed and propagated into the NN in each iteration of the system.

The **Behavioural System** is controlled by the neural process. In the Motivations layer one action is chosen, accordingly to a *roulette* algorithm. Instead, in the Motor System Layer, one neuron controls the linear speed, and the other two the angular speed (See Fig. 3). But, the Motor System, apart from being defined by the Motor System Layer, is also affected by the agents' emotional state (E-Feedback), as showed in Table. 3. Background Emotions are obtained from the analysis of the Goal System (See Table 4), body state evolution. The agent emotional state is processed in parallel and is mirrored into a set Background Emotions. The term is used by Damasio [1] and states for the responses caused by "...certain conditions or internal state engendered by ongoing physiological processes or by the organism's interactions with the environment or both". An important aspect regards the agents' internal representation of the objects. The learning process allows the agent to attribute meanings to the objects. They don't have any internal explicit representation.

Learning is performed by means of an algorithm similar TD-Learning technic, a branch from the traditional Reinforcement Learning Algorithms [26]. One particularity of this algorithm is to associate continuously a Q-Value with each output, that corresponds to the desirability of choosing that action (the predicted reward). The reward received in the future (when the task finishes, successfully or not) is used to update the weights that activated the chosen outputs, through a Back-propagation algorithm. Instead, in our system, outputs (Motivations, see Fig. 4) don't have an associated Q-Value. Rewards depend on the agent actions: they are proportional to the effect of the agent on agents well-being, and their valence (positive or negative) depend on the pleasantness of the new body state. These rewards are received after interacting with objects, reflecting the consequences of the action performed. Then are used to update the weights in the NN using the same technic. In Fig. 3 we present a schematic for the NN configuration.

2.7 Case Study: Implementation of a model for time and dynamic expressiveness in music performance.

Two physiological variables, selected for their influence in actual humans performances [27], *Heart Rate* and *Adrenaline*, control *tempo* and *velocity* (loudness) in the performance of a piece of music [28], reflecting neural activity and emotions valence (whether positive or negative), mirroring the agent's emotional state. *Heart Rate* values modulate the on-times of events within each measure (bar), in this case 4000 ms, with a maximum deviation of +/- 640 ms. *Adrenaline* values modulate events' velocity (loudness) between user chosen limits, in this case, 80 and 127.

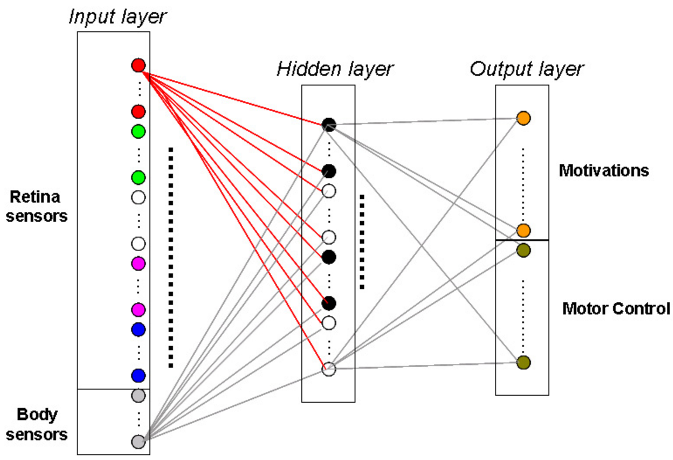

Fig. 3. Neural Network configuration.

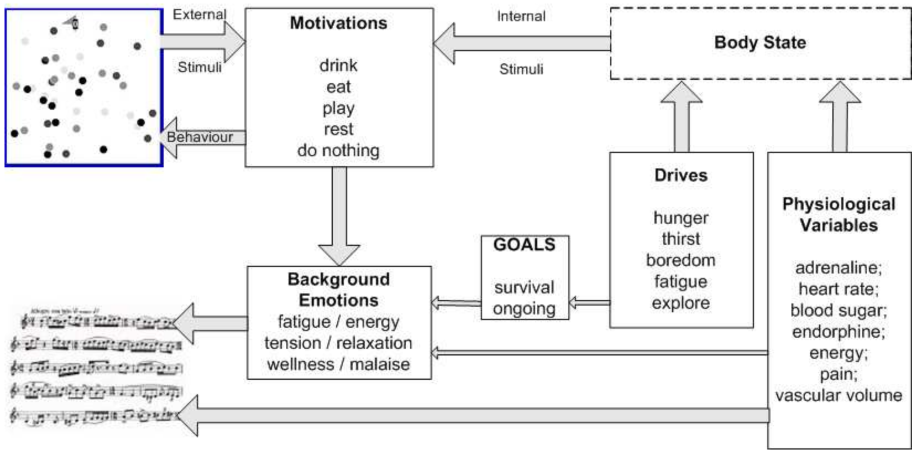

Fig. 4. Emotional System architecture.

3 Results

The simulations aim to analyze the agents' ability to regulate their Homeostasis. A simple metric to use is the Fitness evolution, together with Drives evolution. This way we can identify the emergence of adaptation phenomena, in the current experiment, associations between world stimuli with internal needs. We run the simulations with one single agent, and we created a fitness function that expresses

Physiological Data	Drives	Variation
Blood Sugar	Hunger	metabolism: -K$_{BSugDec}$*speed food: (K$_{BSugInc} * meal$)
Endorphine	Boredom/Excitement	metabolism: +K$_{EndInc}$ toy: (K$_{EndDec}$*meal)
Energy	Fatigue/Energetic	metabolism: -K$_{EnDec}$ bed: (-K$_{EnInc} * meal$)
Vascular Volume	Thirst	metabolism (-K$_{VVolDec}$) water: (K$_{VVolInc}$*meal)
Pain	Withdraw	metabolism (-K$_{PainDec}$) obstacles: (K$_{PainInc}$
Adrenaline	-	arousal and emotions
Heart Rate	-	emotions

Table 2. Physiological Data, Drives, and their dynamnics

Background Emotion	Affected by	E-Feedback
wellness/malaise	survivalGoal	-
relaxation/tension	pain, survivalGoal	reduce/augment *heart rate*
fatigue/excitement	energy, ongoingGoal	reduce/augment *adrenaline*

Table 3. Background Emotions and Emotional Feedback.

Goals	Description
survivalGoal	measures the fitness status of the agent (0%-100%, low fitness-high fitness)
ongoingGoal	measures the amount of actions chosen and successfully achieved

Table 4. Goals.

the agent body state - its *degree of health.*

$$fitness = \left(1 - \frac{1}{n * DriveMaxLevel}\right) \cdot \sum_{k=1}^{n} \cdot |drives_i| \tag{1}$$

3.1 Adaptation

The agent was inserted in a world populated with the objects as referred in Sec.2.2. We evaluated the agent's degree of adaptation (Fitness). Fig. 5 shows the relation between fitness function and the evolution of drives.

Note 1. when fitness goes below 40% agent physiological data is reset to the initial values. That explains the initial picks in the chart, in the first iterations.

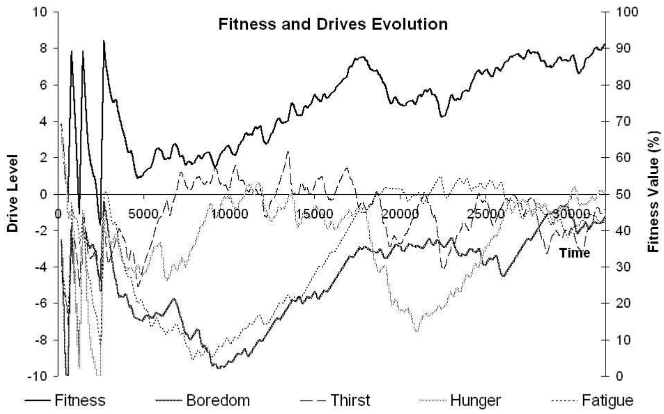

Fig. 5. Static Environment: Fitness and Drives evolution.

3.2 Expressiveness in Music Performance

We collected the data from the simulation in the previous section to control a piece of music [28]. In Fig. 6 we present the first measure of the piece. The anatomy of each note is here controlled by three parameters (MIDI messages): note-number, note-duration (measured in ms), and velocity (loudness). In the original file notes are played every 250 ms. In our piece their duration varies according to *Heart Rate* value(see Fig. 5). Velocity (or loudness) is controlled by the level of *Adrenaline*. We sonify *Heart Rate* by mirroring stable or instable situations, relaxation or anxiety with deviations from original rhythmic structure of each measure of music, and *Adrenaline*, mirroring excitement, tension, intensity, or, in the other hand, boredom, low arousal, by changes in note-velocity (loudness).

Fig. 6. Score: J.S.Bach - *Prelude no I, BWV 846, from the Well Tempered Klavier I.*

Heart Beat	Note duration	Adrenaline	Amplitude	MIDI
71.000	226.387	5.207	92	[145 60 92]
69.263	239.539	9.228	94	[145 64 94]
69.649	246.098	9.652	97	[145 67 97]
69.991	257.054	9.538	97	[145 72 97]
69.770	233.929	9.466	86	[145 76 86]
70.269	264.449	9.962	112	[145 67 112]
70.659	249.279	9.962	98	[145 72 98]
70.548	255.966	10.239	121	[145 76 121]
70.890	237.331	10.335	99	[145 60 99]
70.902	278.871	10.334	102	[145 64 102]
70.908	256.56	10.363	105	[145 67 105]
70.950	250.47	10.288	109	[145 72 109]
71.301	265.184	10.392	85	[145 76 85]
71.323	237.109	10.084	107	[145 67 107]
71.322	261.263	10.078	90	[145 72 90]
71.655	240.51	10.169	112	[145 76 112]

Table 5. Performance data (MIDI messages: [Instrument Pitch Velocity] - Piano.

4 Discussion

Analyzing the results, we can perceive that the agents' evolved towards a well-being state, by self-regulation of the homeostatic process. It is evident in the chart, by looking at the Fitness curve, the overall process or learning an adaptation, suggesting that the agent is capable to adapt itself to the new environment. Fitness tends to stabilize dynamically in higher values, reflecting the successful adaptation. Fig. 5 shows a decrease of the amplitude of the drives as time evolves, although within a certain range, reflecting the agent's ability to respond to its "body needs". Here the agent has not only learned how to adapt to the new environment, but it also did it effectively, maintaining a "healthy behaviour", by self-regulation of the homeostatic process. We used the initial adaptation phase values from two variables to control the performance of our music example, where *Heart Beat* and *Adrenaline* values transpose some of the variations in the agents emotional state. The performance here presented reflects the novel and unstable phase of the agent first "years" of life. The results can be heard at http://cmr.soc.plymouth.ac.uk/ecoutinho/ (link *Polymnia*).

5 Conclusions and Future Work

Analyzing more deeply the system, we could find even that performance in different environmental scenarios, and with different agent metabolism, influenced strongly the emotional states. The model proposed, due to its complexity, consists in a dynamic system where the results are far from being easily predicted with analytical methods. Even though, we did present some solid results, mostly exploring the agents at the individual level.

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